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Experimental Progress toward EIT in an Atomic Beam

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Abstract
EIT (Electromagnetically Induced Transparency) is a quantum optics phenomenon that occurs under specific conditions during a photon-atom interaction. Under such conditions, slow-light may be produced as a by-product of this effect. The purpose of this research is to adapt previous work on rubidium atoms in vapor cells to lithium atoms in a thermal beam. By doing so, the hope is to better understand the limitations of slow light and produce better results by eliminating atomic collisions within the system.

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Senior Thesis

Experimental Progress toward EIT in an Atomic Beam

by

Sean E. Tilton

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The report of the investigation undertaken as a
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the Department of Physics

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ABSTRACT

EIT (Electromagnetically Induced Transparency) is a quantum optics phenomenon that occurs under specific conditions during a photon-atom interaction. Under such conditions, slow-light may be produced as a by-product of this effect. The purpose of this research is to adapt previous work on rubidium atoms in vapor cells to lithium atoms in a thermal beam. By doing so, the hope is to better understand the limitations of slow light and produce better results by eliminating atomic collisions within the system.

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TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Electromagnetically Induced Transparency (EIT) is a phenomenon in which two beams of light cancel the absorption within a material through quantum interference. The classical analogy is to imagine a mass hanging from a spring. At resonance, the mass oscillates up and down very rapidly. If a second spring is attached at the bottom and driven with the same frequency but opposite phase of the top spring, the two resonances will interfere destructively and the motion will be cancelled out. In the case of EIT, left and right circularly polarized light drive two transitions with the same frequency. The electric fields from the light are of opposite phase, and the electron stays put. This means that the absorption is cancelled out and there will be a greater transmission of light through the medium. In our experiment, if the absorption is cancelled out, fluorescence will not occur and we will see a decrease in signal.

One of the most interesting side effects of EIT is the production of slow light. As light travels through a medium, different frequencies travel at different speeds. This relationship is called the dispersion and represents the change in index of refraction over a change in wavelength. When EIT occurs, the dispersion increases and produces a much higher effective index of refraction. As a result, the circularly polarized light is slowed down significantly.

The index of refraction in EIT is limited by the collisions of atoms within the material. While collisions are a concern in vapor cells, atomic beams are collision free. In addition to this advantage, atomic beams are unidirectional. This means that when the atomic beam intersects a perpendicular beam of light, first order Doppler shifts are eliminated. Doppler shifts occur when the frequency of light changes as the atoms move toward or away from the light. In a vapor cell, the thermal energy of the atoms causes

them to move toward and away from the laser. The atoms moving toward the laser experience a higher frequency than the atoms moving away from the laser. This broadening of frequency causes a loss of resolution in the transitions.

II. THE LITHIUM ATOM

A. Photon and Atom Interactions

Lithium consists of three electrons orbiting a nucleus comprised of three protons and three or four neutrons. The electrons may occupy discrete energy levels, which are described by the *principal quantum number, n*. A photon can be used move an electron from a lower state to a higher state through a process called *absorption*. During this process, the atom can absorb a photon when the photon has energy equal to the difference in energy levels. The energy of a photon is given by

$$E = \hbar\omega \tag{1}$$

where ħ is Planck's constant divided by 2π and ω is the angular frequency. If a beam of light goes through a gas of atoms, the intensity of the light will diminish when absorption occurs. When the light is off-resonance and absorption does not occur, the laser beam will have a greater intensity.

Higher energy states are inherently unstable. As a result, the electron will decay back down to a lower state after a brief period of time. The excess energy is expelled in the form of another photon with an energy that depends on which energy level the electron decays down to. This process of emitting a photon is called fluorescence. The light emitted from the atoms scatters in all directions.

A third process between atoms and photons may occur when the atom is already in an excited state. A photon with energy equal to the difference in energy between the excited state of the electron and any lower state will cause that electron to drop down to

that lower state. This process, called *stimulated emission*, will cause a second photon to be emitted with the same energy as the incident photon. This interaction is a key component in the functionality of lasers and will be discussed in a later section.

In addition to the *n* quantum number, there is an *l* quantum number that represents the orbital angular momentum of the electron. The possible values of *l* are $l = 0, 1, 2, \dots, n-1$. There is also an m_l quantum number that can have values of $m_l = -l, -l+1, \dots, l-1, l$. Electrons also possess an intrinsic angular momentum called *spin*, which is denoted using the letter *s*. All electrons have a spin of ½. The spin quantum number, m_s, has values of $m_s = -s, -s+1, \dots, s-1, s$.

As it turns out, there are several effects that both shift and split the energy levels. One such correction is called spin-orbit coupling. This correction arises from the effects of relativity as well as the interaction between the electron's spin and orbital angular momenta. These effects change the potential energy in the Schrodinger equation, and as a result, shift and split the energy levels. This splitting is known as *fine structure*. The total angular momentum, *J*, is the combination of *l* and *s*. In fine structure, the possible values of *J* go from $l + s$ to $|l - s|$.

A second splitting occurs when the magnetic moment of the nucleus and its interaction with the electron is considered. This produces a similar effect known as *hyperfine structure*.[1] Lithium-6 has a nuclear spin, *I*, of 1 and lithium-7 has a nuclear spin of 3/2. The *F* quantum number describes the interaction between *J* and *I*. Similar to *J*, the possible values of *F* are $J + I$ to $|J - I|$. Ultimately, there are eight possible states for the n=2 energy level of lithium. The states are $2s_{1/2}$ (F=1), $2s_{1/2}$ (F=2), $2p_{1/2}$ (F=1), $2p_{1/2}$ (F=2), $2p_{3/2}$ (F=0), $2p_{3/2}$ (F=1), $2p_{3/2}$ (F=2), and $2p_{3/2}$ (F=3).

B. Transitions in Lithium

In lithium, there are three groups of transitions of the valence electron that are of interest. If we can find these three groups, we can use references to identify the individual transitions within these groups. These groups contain both lithium-6 and lithium-7 energy lines. For EIT, we are trying to locate the D_1 lines of lithium-7. The D_1 lines are the transitions from the ground state to the first excited states from J=1/2 to J'=1/2.

The specific transition we are seek is the $2S_{1/2} \longrightarrow 2P_{1/2}$ transition from F=1 to F'=1

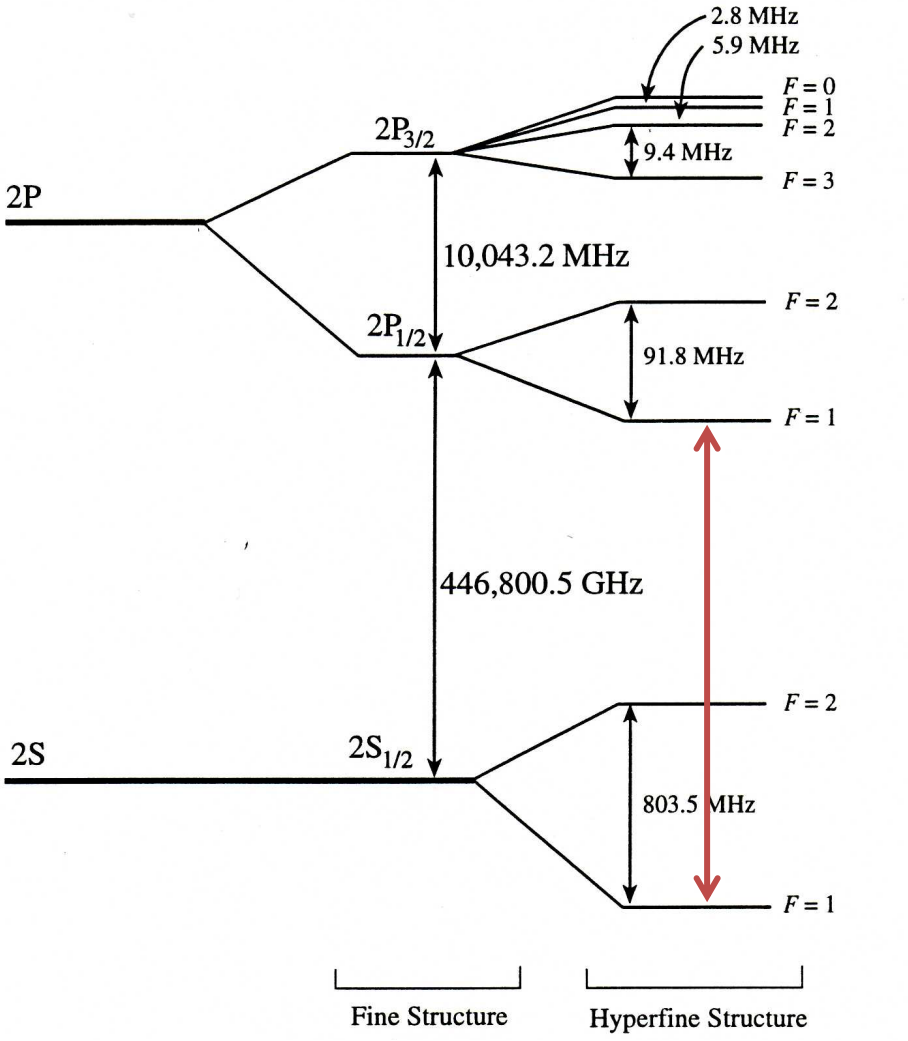

FIG. 1. Lithium-7 fine structure and hyperfine structure transitions. Adapted from Windell Oskay's thesis.[2] Our desired transition is in red.

in lithium-7. This transition is shown in FIG. 1. Due to the Zeeman Effect, each of the F=1 states will split into three states which are necessary for EIT. The possible states are m_F = -1, 0, 1.

III. APPARATUS

In the next section, we will discuss the apparatus required for our experiment. On the next page contains a diagram of all the equipment that we used on the optical table. We will attempt to explain the function of all these pieces and how they are used to achieve EIT.

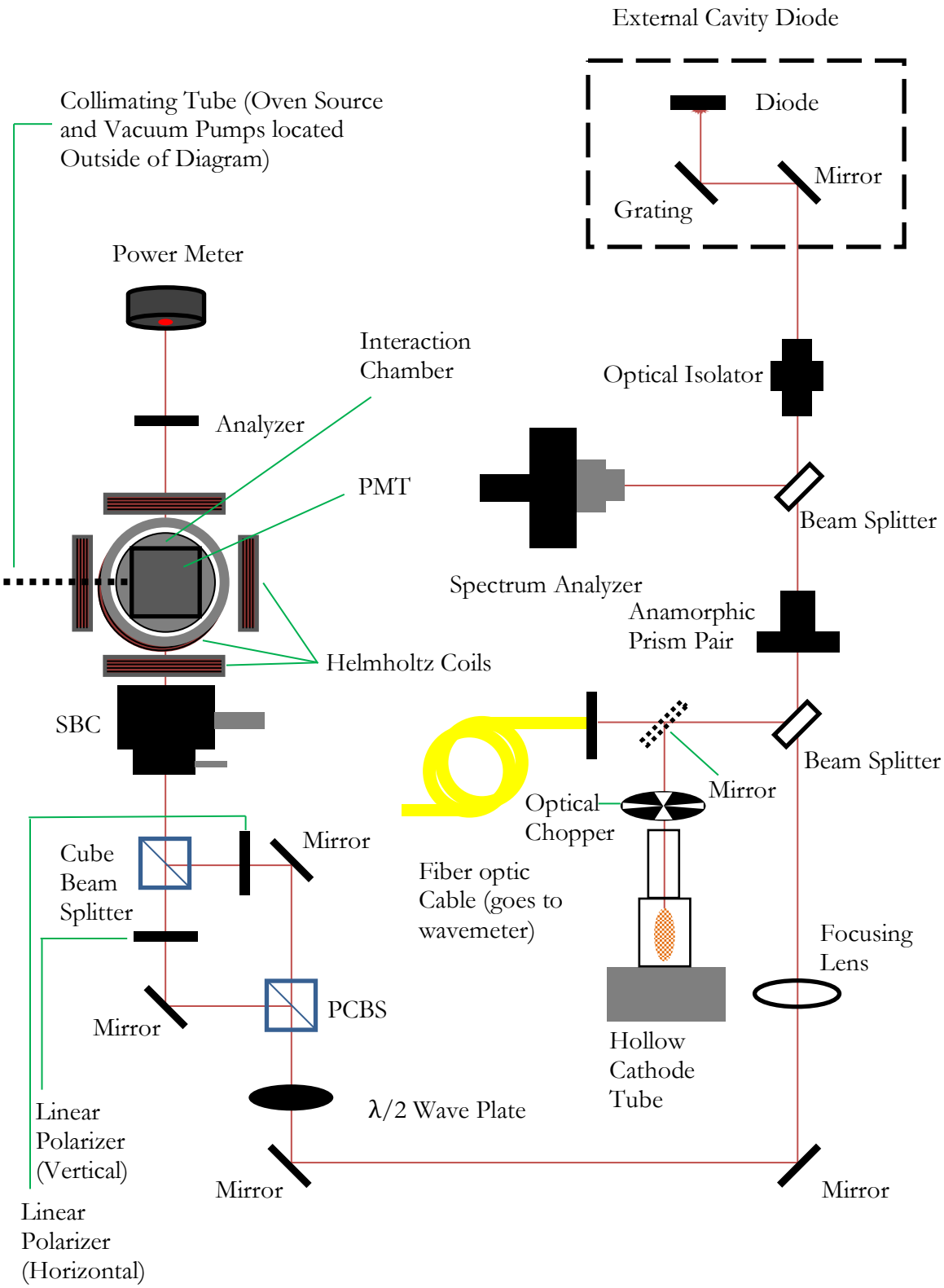

FIG. 2. A block diagram of the apparatus. The mirror represented with dashed lines is removed when using the fiber optic cable, and installed when using the Hollow Cathode Tube. This figure is referenced often in the next section.

A. Vacuum Chamber

A vacuum chamber is used to house the atomic beam. This system is actually comprised of an oven chamber and an interaction chamber. These two containers are connected by a collimating tube where the atomic beam travels from the oven chamber into the interaction chamber.

1. Vacuum System

There are two parts of our vacuum system that are used to create an atomic beam. The first is a roughing or mechanical pump. We use a Welch Model 1402 Duo-seal vacuum pump, which can bring the pressure of the system down to about 30 mTorr with about an hour of pumping. This has oil-sealed rotary vanes which help to pump the air out of our system. After this has brought the pressure below 30 mTorr, we employ the use of a diffusion pump.

The diffusion pump contains a heated plate at the bottom and water-cooled walls. Inside a container within the diffusion pump, the heated plate, or boiler, vaporizes oil that forced out of the container. The vapor exits through nozzles that direct the vapor downward. This vapor then collides with air molecules and "catches" them for a brief moment. The air molecules soon separate from

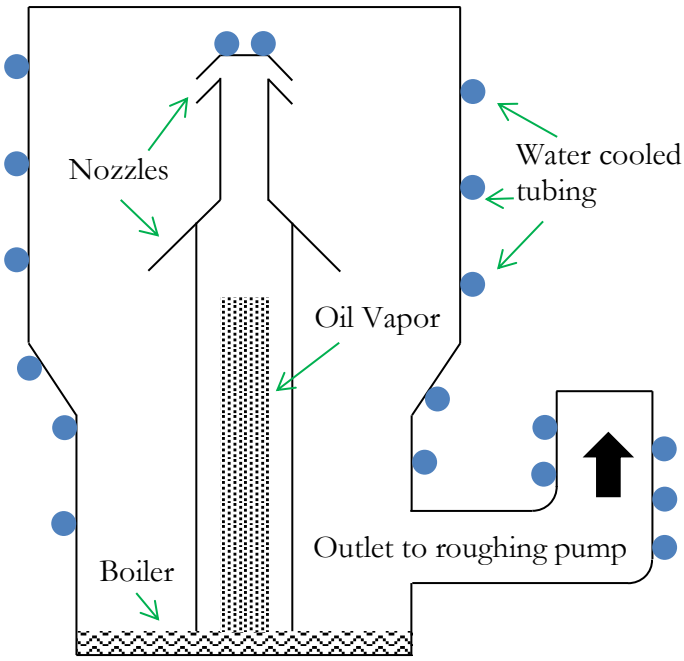

FIG. 3. Cross section of a diffusion pump.

the vapor but maintain a downward momentum from the collision. This creates a higher pressure toward the bottom of the pump, forcing the air toward the outlet where it is pumped out by the roughing pump. Although there is a lower pressure above the air molecules, the continual vaporization of the oil pushes the air downward, preventing the air from rising. The oil vapor condenses after colliding with the cooled outer wall and returns to the boiler at the bottom of the diffusion pump.[3] Our diffusion pump is capable of reducing the pressure down to about 6×10^{-7} Torr at room temperature.

To measure the pressure, we use two different instruments. We use a thermocouple gauge to measure the foreline pressure. The thermocouple gauge is essentially a resistor with constant current running through it. The temperature of the wire changes as the pressure changes. The resistance of the wire changes due to this temperature change. As a result, the voltage across this resistor can be measured and converted into a pressure. For pressures inside the oven chamber, we need a more sensitive measuring device. We use an ionization gauge to accomplish this. Inside this gauge, a heated filament emits a constant stream of electrons. These electrons collide with the gas inside and ionize these molecules. A negatively charged collector then attracts the positive ions. The positive current caused by this interaction represents the particle density which can be used to calculate the pressure if all other parameters (such as temperature) are held constant.

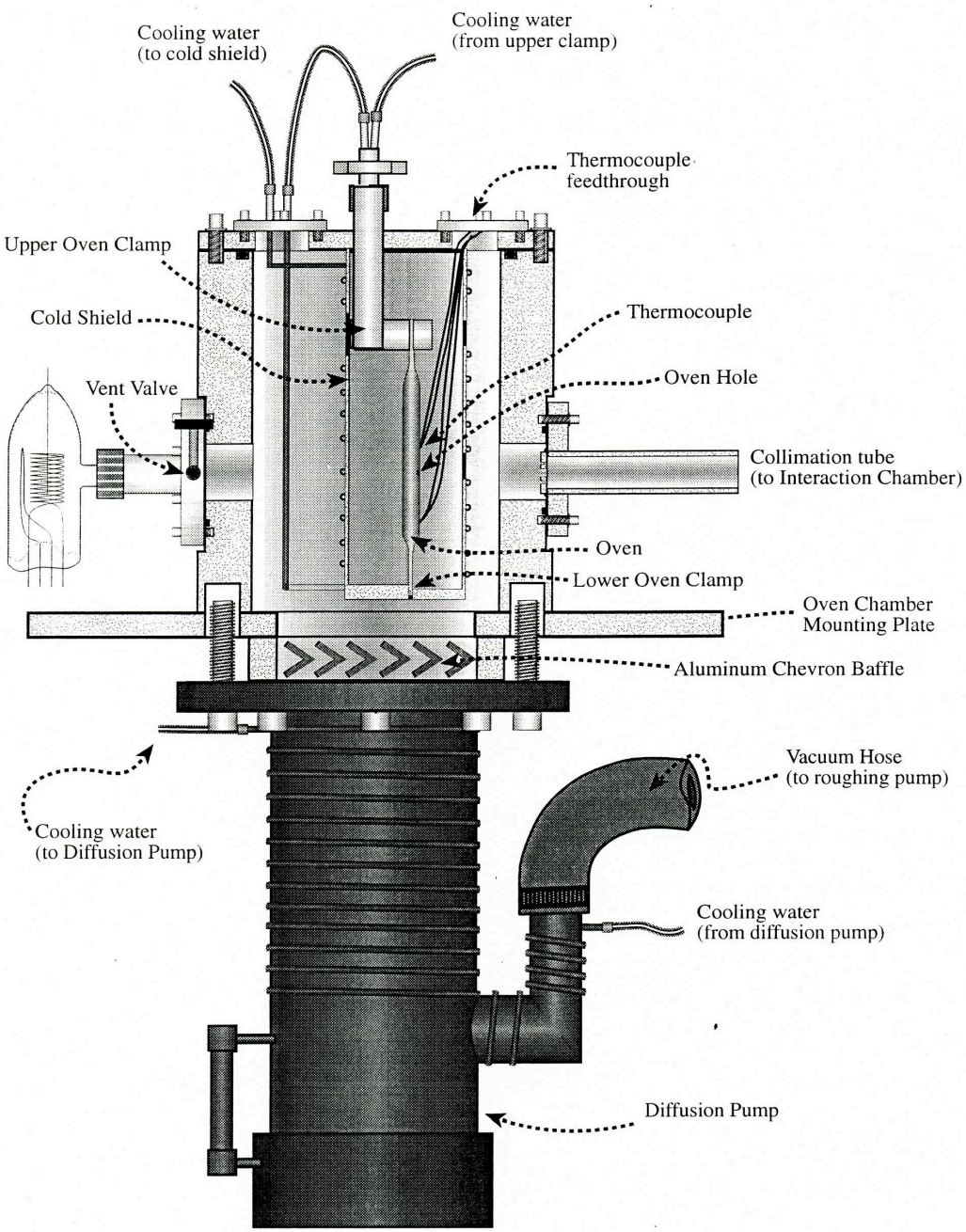

FIG. 4. A diagram of the vacuum system. Adapted from Windell Oskay's thesis.[2]

2. Oven

Lithium vaporizes at a temperature of 180.5°C. In order to produce fluorescence, we need even higher temperatures to form an atomic beam. We accomplish this with the use of a resistance-heated tube oven. We fill a 0.5 inch diameter, 8.0 inch long, stainless steel tube with approximately 1 gram of lithium and crimp the ends. The tube has a hole

with a 1 mm diameter from which the vaporized lithium emerges. By running several hundred amps of AC current through our tube, the resistance of the steel produces the heat necessary to vaporize the lithium. We typically run 2-4 amps through the primary of a homemade step-down transformer to increase the current to about 200 amps. When operating the oven, we need to monitor the chamber pressure to ensure back streaming does not occur in the diffusion pump and oven chamber. When raising the temperature slowly, we typically begin to see some signals around 400-450°C. Our typical operating range however, is closer to 550-650°C.

3. Atomic Beam

One useful calculation for our atomic beam is the lifetime of the oven. According to Ramsey,[4] the rate of atoms coming from the oven is given by

$$Q = \frac{1}{4} n \bar{v} A_s, \tag{2}$$

where n is the number of atoms per unit volume in the oven, $\bar{v}$ is average speed of the atoms, and A_s is the area of hole in our oven tube. The area can be approximated as a circle such that

$$A = \pi r^2 = \pi \left(\frac{d}{2}\right)^2. \tag{3}$$

The diameter of our oven hole is 1 mm. We obtain n from the ideal gas law,

$$p = nkT. \tag{4}$$

In this equation, p is the vapor pressure of lithium, k is Boltzmann's constant, and T is the absolute temperature of our oven. Furthermore, we can obtain the average speed of the particles by using the results from the Maxwell-Boltzmann speed distribution:

$$\bar{v} = \frac{2}{\sqrt{\pi}}\sqrt{\frac{2kT}{m}} = \sqrt{\frac{8kT}{\pi m}}. \quad (5)$$

The mass of a lithium atom is ($6.941\text{u} \times 1.6605 \times 10^{-27}$) kg. Armed with these equations, we can now solve for the lifetime of our oven

$$\tau = \frac{N}{Q} = \frac{m/M}{Q} \quad (6)$$

where *N* is the number of atoms in our oven. To find this number, we take the mass of our sample, *M*, (approximately 1 gram) and divide it by the mass of a lithium atom. Based on these equations, the lifetime of our oven will depend on the temperature and the vapor pressure. We can find the vapor pressure as a function of temperature using the following equation from the Canadian Metallurgical Quarterly:[5]

$$log(p/\text{Pa}) = 5.006 + A + BT^{-1}. \quad (7)$$

For solid lithium, A=5.667, and B=-8310K. From our reference, there are generally two other terms in this equation. In the case of lithium these two terms are zero. Based on this information, our lifetime is roughly 233 hours at an oven temperature of 550°C (where we experimentally begin to see clear fluorescence). At 600°C, our lifetime diminishes to 63 hours. If we want even stronger fluorescence signals, we might heat our oven to a temperature as high as 700°C, but we would only be able to operate at this temperature for about 7 hours.

An important parameter for EIT is the beam density of our atomic beam in the interaction chamber. According to Ramsey[4], the beam current (the number of particles hitting the area of a detector per unit time) is given by

$$I = \frac{1}{4}\frac{A_d}{{l_0}^2} n\bar{v}A_s \tag{8}$$

where A_d is the area of the detector and l_0 is the distance away from the source. The beam intensity (number of particles per unit volume per unit time) is therefore

$$J = \frac{I}{A_d} = \frac{1}{4\pi {l_0}^2} n\bar{v}A_s. \tag{9}$$

To get the beam density in the interaction chamber, we simply need to divide by the speed of the particles:

$$n_i = \frac{J}{\bar{v}} = \frac{nA_s}{4\pi {l_0}^2}. \tag{10}$$

We made a rough estimate of the distance between the source and the interaction chamber and found the distance was about 0.44 meters. Using the same data from Canadian Metallurgical Quarterly, we found that the beam density at the laser is 1.05×10^{14} particles per meter cubed at 550°C.

Another important requirement to keep in mind is optical pumping. This process transfers angular momenta of light to the atoms. We want to ensure that our atoms interact with the laser long enough so that photons can excite most of the lithium atoms. We can make an estimate of the time that the atoms in the beam intersect with the laser beam using

$$t = \frac{d}{\bar{v}} \tag{11}$$

where the width of the laser beam, *d*, is roughly 2 mm and $\bar{v}$ is calculated by equation (5). Using this information, we calculated the interaction time to be 1.23×10^{-6} seconds. Based on a reference table from Corney[6], the radiative lifetime of lithium is 2.7×10^{-8}

seconds. This indicates that our thermal beam interacts with the laser for many life cycles, and should experience optical pumping.

Table I. A summary of the results from this section for three temperatures.

T (°C)	T (K)	n_{oven} (m^{-3})	$n_{\text{inter cham}}$ (m^{-3})	τ (hours)
550	823.15	3.33×10^{20}	1.053×10^{14}	232.76
600	873.15	1.19×10^{21}	3.76×10^{14}	63.33
700	973.15	1.01×10^{22}	3.24×10^{15}	7.03

4. The Interaction Chamber

The interaction chamber is where the laser and the atomic beam meet. The laser enters and exits the chamber through two windows from CVI that possess an anti-reflection coating designed for 671 nm. Additionally, the windows are angled so that any reflections do not interfere with the laser beam. This is important to note for alignment since this also causes the light passing through the windows to bend. In order to minimize this effect, we have oriented each window opposite from each other so that the second window can slightly correct the deflection caused by the first window.

An interaction tube is placed in the interaction chamber and runs from one window to the other. The interaction tube eliminates unwanted light and makes the fluorescence easier to detect. According to Windell Oskay's thesis,[2] the tube is 0.5 inch in diameter and has a 0.125 inch bore for the laser beam. Two additional, perpendicular holes allow fluorescence upward, and to allow the atomic beam to pass. The interaction tubes helps to collimate the atomic beam so that it is perpendicular to the laser.

Above the interaction tube is a photo multiplier tube (PMT) that detects the fluorescence. When fluorescence occurs, light is emitted upward through the interaction

tube and into the PMT. The PMT amplifies the photocurrent, which is converted to a voltage by a current-to-voltage op-amp configuration and measured by an oscilloscope.

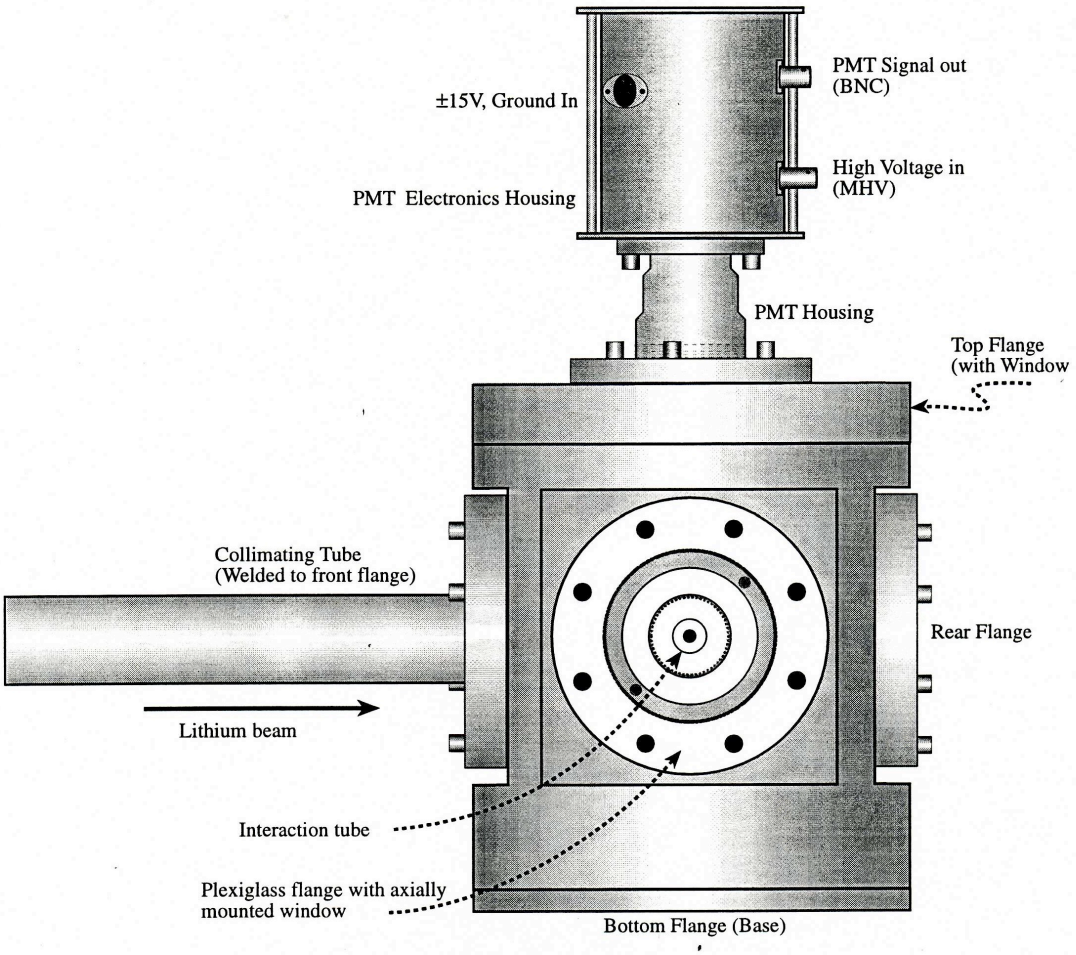

FIG. 5. A diagram of the interaction chamber from Windell Oskay's thesis.[2]

5. Unwanted Magnetic Fields

A vital condition for EIT to occur is the absence of electric and magnetic fields in the interaction chamber, where the laser beam intersects the atomic beam. There are two types of magnetic fields we need to be concerned about. There are constant magnetic fields, which we will call DC magnetic fields, and oscillating magnetic fields, which we will call AC magnetic fields. In order to reduce the DC fields, three sets of Helmholtz coils are used to control the magnetic fields in the x, y, and z directions. A three-axis gauss probe is used to measure the magnetic field in the center of the interaction chamber, and a constant-current power supply can be used to run the Helmholtz coils and the negate the unwanted environmental magnetic fields.

(a) DC Fields

The three sets of Helmholtz coils are arranged around the outside of the interaction chamber. Each set of coils is comprised of two identical electromagnets that require a separation equal to the radius each of the coils. The advantage of using Helmholtz coils is their ability to create uniform magnetic fields over a relatively large volume. The set of coils controlling the vertical magnetic field are called the Fine Coils I, which have a radius and separation of 8 cm. These coils are designed to produce 5 gauss when 1 A is used. The Fine Coils II run control the magnetic field in the direction of the laser beam. These coils have a separation of 12 cm and produce 5 gauss at 1.1 A. Lastly, the Heavy Field Coils are separated by 10 cm and produce 100 gauss when 4.75 A are used.

Using a Lake Shore 460 gaussmeter, we were able to find constant environmental fields which we called DC magnetic fields. We set the probe so that $+x$ was the direction

toward the source of the laser beam, $+y$ was the direction upward toward the PMT, and $+z$ was the direction toward the source of the atomic beam. After taking several measurements, we found that the external magnetic field was $(0.0130\hat{x} + 0.0520\hat{y} + 0.08217\hat{z})$ mT. We used a Keysight E361A power supply to power the Helmholtz coils and eliminate these DC fields. In order to create zero magnetic field, we used the +6V output to produce 0.004A in the x direction, the +25V output to produce 0.013A in the z direction, and the -25V output to produce 0.027 A in the y direction.

(b) AC Fields

After setting up the experiment to observe EIT, we expected the fluorescence peaks to be very narrow when subjected to zero magnetic field. The larger width of the peaks we observed could be attributed to the Zeeman Effect, which splits the energy levels in an atom when an external magnetic field is applied. Using a Meda μMAG-03 fluxgate magnetometer, we found that while the DC environmental magnetic fields seemed to be reasonably eliminated, an AC magnetic field source from our oven was disrupting our results. We initially believed that the AC magnetic fields came from the two current carrying wires (which carry several hundred amps) that heat the oven. Upon observing the AC magnetic fields and the effects of magnetic shielding, however, it became clear that the current running through the oven itself was significant source for these magnetic fields and the effects from the current carrying wires was very small. The negligible magnetic fields from the twisted wires could be attributed to the fact that the two currents flow in opposite directions, causing the magnetic fields to cancel each other out.

We considered several solutions to this problem: the oven could be moved farther away until the magnetic field became weaker, one of the Helmholtz coils could be coupled with to the AC line to cancel out this effect, or magnetic shielding could be installed to reduce the fields. Each of these solutions has its merits as well as its drawbacks. The main concern with the first solution is that the increased distance of the oven would reduce the intensity of the atomic beam, making the observation of EIT more difficult. As for the second solution, coupling one of the Helmholtz coils would be very difficult if the AC magnetic fields have more than one component (requiring the coupling of two or three sets of Helmholtz coils). Finally, magnetic shielding loses effectiveness when the shielding has gaps, holes, or edges. Trying to shield the interaction chamber would be less effective because we would have to drill holes for the laser beam as well as atomic beam. The alternative would be to cut planar sheets of shielding around the

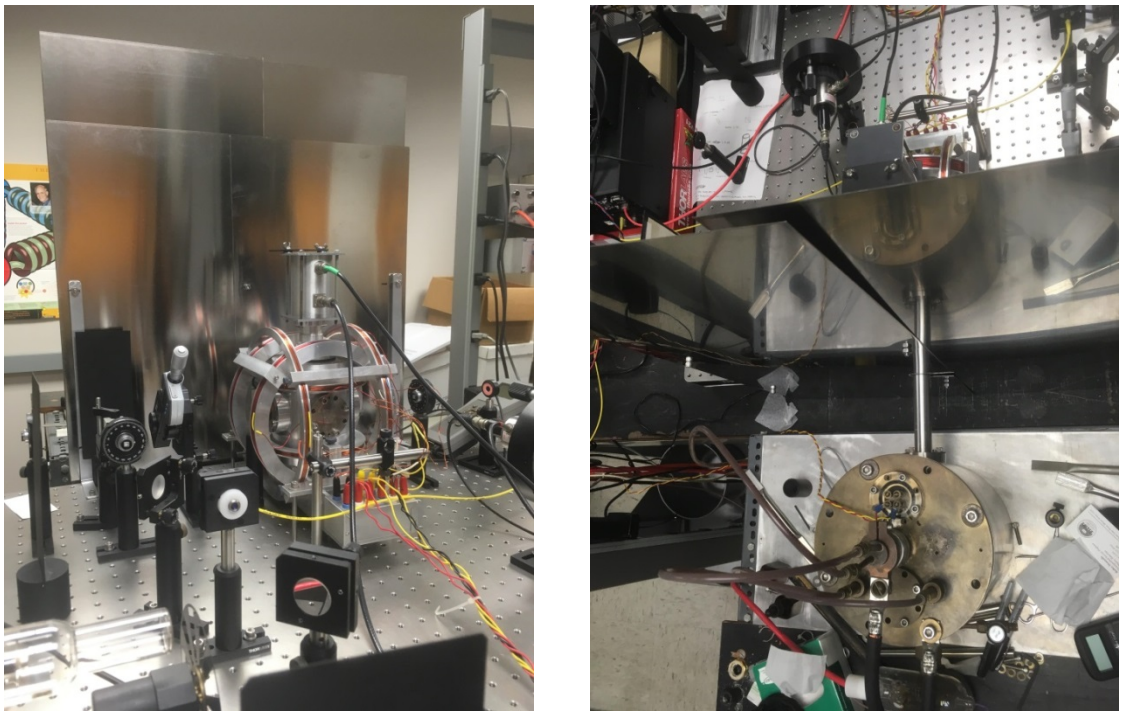

FIG. 6. Pictures of the magnetic shielding. There are two layers with a gap to wrap around the collimation tube.

atomic beam, which would allow magnetic fields to "creep" around the edges.

Weighing these different options, we chose to use magnetic shielding around the collimating tube to eliminate AC magnetic fields. Although a gap in the magnetic field for the collimation tube was necessary, we hoped using two sheets of Conetic magnetic shielding from Magnetic Shield Corporation would be enough to lower the magnetic field for our purposes. After setting up the magnetic shielding, we measured an AC magnetic field under 20 milligauss. We then found that our step-down transformer also contributed to this magnetic field. We therefore replaced the 2/0 AWG cables with a longer version to move the transformer several feet away from its previous position. This reduced the magnetic field to less than 5 milligauss.

B. Laser

In order to excite the lithium atoms in our experiment, we utilize a particular type of semiconductor diode laser. The acronym, laser, stands for "Light Amplification by the Stimulated Emission of Radiation," and a principal advantage of lasers is their ability to produce light beams of a narrow band of frequencies. In the quantum depiction of an atom, electrons have discrete energy levels and may not have any energy between these discrete levels. In certain solid materials, the electrons may detach from the nuclei and collectively roam about the material. In such a case, the discrete energy levels become smeared into energy bands. There are still gaps in energy range for the electrons, but the electrons may have any energy within these bands. Insulators are materials where a band is completely filled and a great amount of energy is needed to excite any electrons across the energy gap into the next band. Conductors, on the other hand, have bands that are only partially filled and require only a little energy to excite any electrons.

P-type materials are insulators that have been doped with electron holes while n-

type materials are semiconductors that have been doped with extra electrons. When a p-type material and an n-type material are put together, some of the excess electrons migrate over to the p-type material and some of the electron holes migrate to the n-type material resulting in an area that is called the "depletion zone." Due to this depletion zone, the PN-junction must be forward biased, meaning that electrons may only flow in one direction. As current runs through this diode, electrons fill the holes and photons are emitted as a result.[1]

Population inversion is a condition that requires at least half of the atoms in a material to be in an excited state. As a result, an incident photon may collide with an excited atom and produce stimulated emission. In that case, the electron in the excited atom will transition to a lower energy level and emit a photon. This may only occur if the first photon has energy equal to the difference in energy levels of the excited state and the lower state of the atom. The emitted photon will have the same energy (and therefore same frequency) of the incident photon. The new photon will interact with another excited atom and continue this process of amplification. Lasers require population inversion to operate properly. Without this condition, the diode will still emit light, but the emitted light will be incoherent.

Diode laser typically have two reflective surfaces to provide a cavity in which the energy can build up. One side reflects nearly 100% of the light while the other side reflects only most of the light, allowing some of the light to be transmitted. For an external cavity diode laser (ECDL) however, an antireflection coating is applied to the second end of the cavity so that no light is reflected. Instead, a grating is placed outside of the cavity, where some of the emitted light can be diffracted back into the diode, and the rest of the light is reflected into a mirror. In this case, it is the grating that forms one end of the cavity outside of the diode; hence the name external cavity diode laser. Our

ECDL is set up in the Littrow Configuration, meaning the grating is placed in a way such that the angle of the incident ray is equal to the angle of the diffracted ray, measured from the normal to the grating. The position of the grating determines the wavelength of the laser.[7]

There are two adjustment screws used to adjust the external cavity. The first is a course-adjustment screw that can be turned using a ball driver. Using a calculation from Matt Davis's thesis,[8] we found that 0.14 rotations of the screw corresponded to a change in wavelength of about 1 nm. A second screw keeps the incident and diffracted beam in the same plane, and therefore controls the amount of feedback from the grating to the diode. The coarse adjustment screw is too sensitive be adjusted by hand. Instead, a voltage is applied to a piezo electric stack which expands or contracts depending on the voltage applied. A control box is used to adjust the current applied to the piezo electric transducer (PZT).

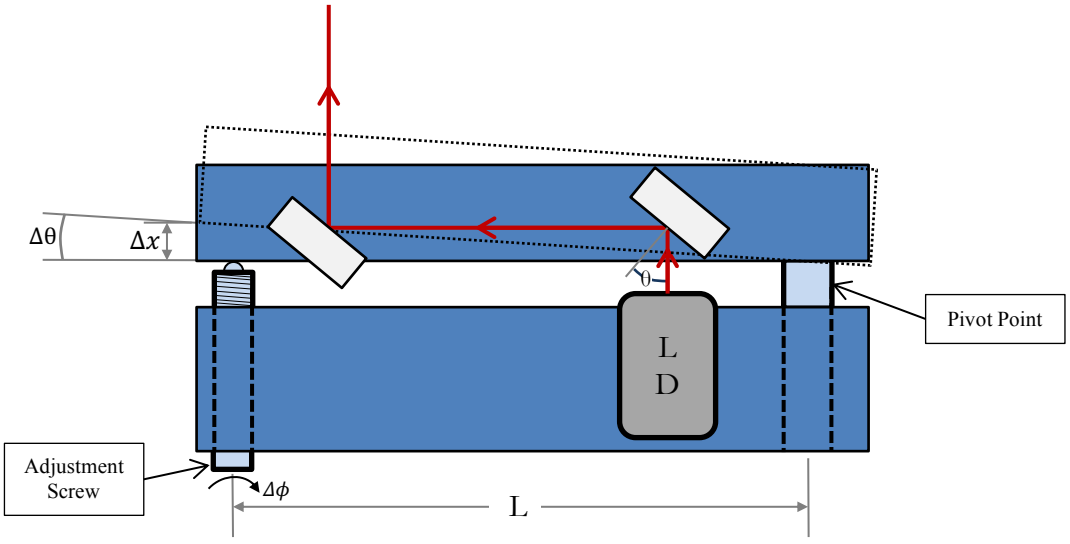

FIG. 7. Diagram of ECDL from Matt Davis's thesis.[8] The PZT is located at the tip of the adjustment screw.

The operating frequency of the laser is also affected by a Thor Labs LDC 205 laser diode controller and a Thor Labs TED 200 temperature controller. A thermoelectric

cooler resistor changes the temperature of the ECDL. The temperature is monitored by a thermistor in the ECDL housing. The temperature takes 15 minutes or so to stabilize. The current controller sets a limit to the current to prevent damage to the diode, and can increase or decrease the current going through the diode. The control box also can change this current with a finer adjustment.

The voltage across the PZT and current through the laser diode are swept back and forth continuously over time. Over a limited range, two slopes can be formed from the output frequency and the supplied voltage of the PZT and the current controller. When these slopes are aligned, the laser will scan smoothly. When the slopes are misaligned in some way, the laser will jump back and forth between two (or more) different frequencies and behave erratically. Both curves can be changed by adjusting the bias (that affects the "y-intercept") and the gain (that changes the steepness of the slope).

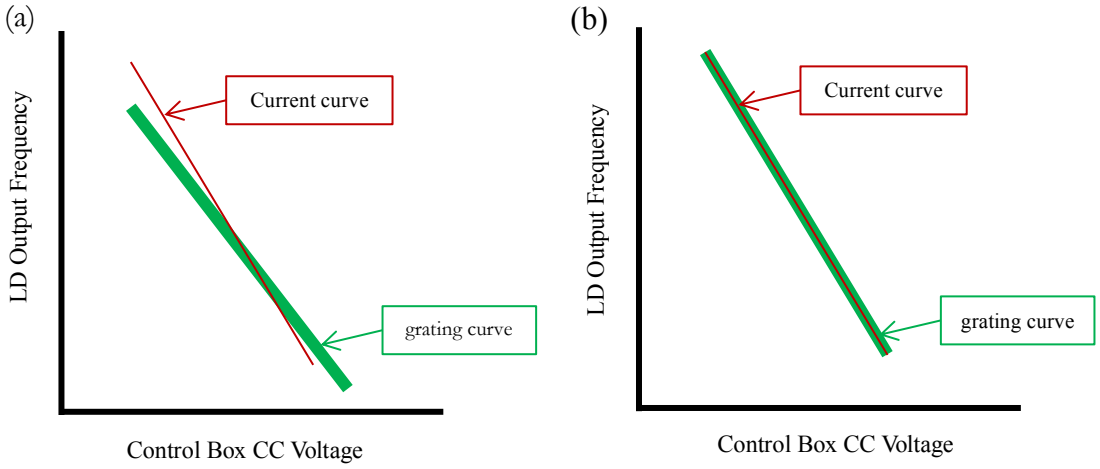

FIG. 8. In part (a), the two curves are misaligned. In this case, there are two possible output frequencies from the current curve and the grating curve. The laser will hop between the two different frequencies at the either end of the scans. In this case, the gain of one or both curves should be adjusted so that the slopes align. The curves should mimic part (b). When these two curves overlap, the laser will sweep smoothly. Adapted from Matt Davis's thesis.[8]

C. Optical Components

1. Wavemeter

Using spectroscopic data from NIST as a guide,[9] we were able to find the transitions among the n=2 states of lithium near 670.8 nm with the help our Burleigh WA-2500 Wavemeter Jr. The wavemeter measures the wavelength using an interferometer. The laser beam enters the wavemeter through a ThorLabs single mode fiber optic cable, where the beam is then separated using a beam splitter. The beams are reflected by mirrors and recombined into a detector. This creates an interference pattern of bright and dark fringes. One of these mirrors moves back and forth to vary the path length difference, which causes the fringe pattern to shift. A detector counts fringes from the interference, and the wavemeter calculates the wavelength of the laser.

In order to produce accurate results, the wavemeter has to be calibrated using a Helium Neon laser, which has a very reliable wavelength of 632.99 nm in vacuum. The wavemeter accounts for the index of refraction for air and can display the wavelength in a vacuum. A round beam shape is another necessary condition for the wavemeter to function. The laser beam produced by the ECDL is not round enough for this purpose, so an anamorphic prims pair is employed to stretch the beam in one direction. After the prism pair, the width of the beam is roughly the same as its height. After the right beam shape is achieved, we adjust the fiber optic cable so that there is enough light for the wavemeter to operate.

Although the wavemeter is very useful for getting a "ballpark" estimate of our wavelength, it is not very accurate for changes in wavelength smaller than 0.1 nm. It also cannot accurately measure wavelengths while the laser is scanning (changing frequency) so the laser must stay at a constant frequency while the wavemeter is being used. The wavemeter has a useful feature that replaces the last digit in the display with a hyphen

when it has difficulty calculating the wavelength. In our experiment, this is not a flaw with the wavemeter, but an indication that our laser is "multi-moding" or hopping back and forth between two similar wavelengths. This indicates that our laser is not tuned properly and that something must be adjusted.

2. Hollow Cathode Tube

Our experiment differs from previous work done with EIT at Lake Forest in that we are observing the fluorescence of atoms as opposed to the absorption of a laser beam. With our current set up, lithium fluorescence signals are very small and difficult to detect due to background noise. As a result, we often use the averaging feature on the oscilloscope to make the signals clearer. A drawback to this technique is that it takes much more time to collect a scan. This delay makes the tuning of our laser cumbersome when we are trying to find the desired transitions in lithium. In addition, we have a limited supply of lithium in the oven that forms the atomic beam. Replacing the oven is time consuming.

For these reasons, it is useful to have a test apparatus that allows us to quickly set our laser to the desired wavelengths. We identify these transitions using a hollow cathode tube. A hollow cathode tube is a glass tube that contains a cathode and an anode surrounded by a buffer gas of neon. Our hollow cathode tube contains lithium in the cathode and makes use of the optogalvanic effect. As current runs through the tube, the electrons collide with the neon gas, which becomes ionized. The ionized atoms are accelerated by the electric field toward the cathode where the gas ions collide with the

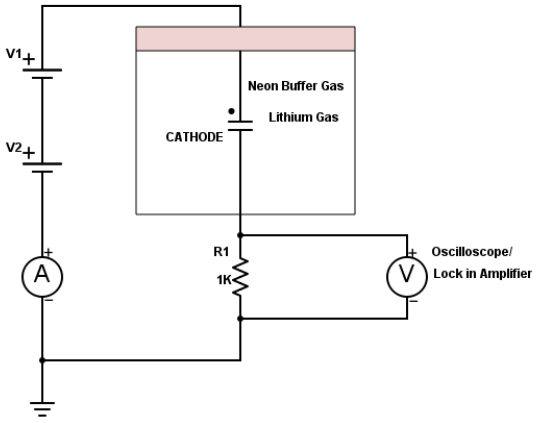

FIG. 9. Schematic of Hollow Cathode tube.

lithium in the cathode, causing the lithium to sputter. This means that the lithium atoms are emitted into an atomic vapor. When photons excite the lithium atoms inside the tube, the lithium atoms become easier to ionize and a noticeable increase in current can be measured.[10] This is the optogalvanic effect. It may be used for spectroscopy. We use two HP E3612A power supplies in series to produces a steady current of about 12 mA. Although this signal is small, it can be detected using a lock-in amplifier, which monitors the voltage across a sense resistor.

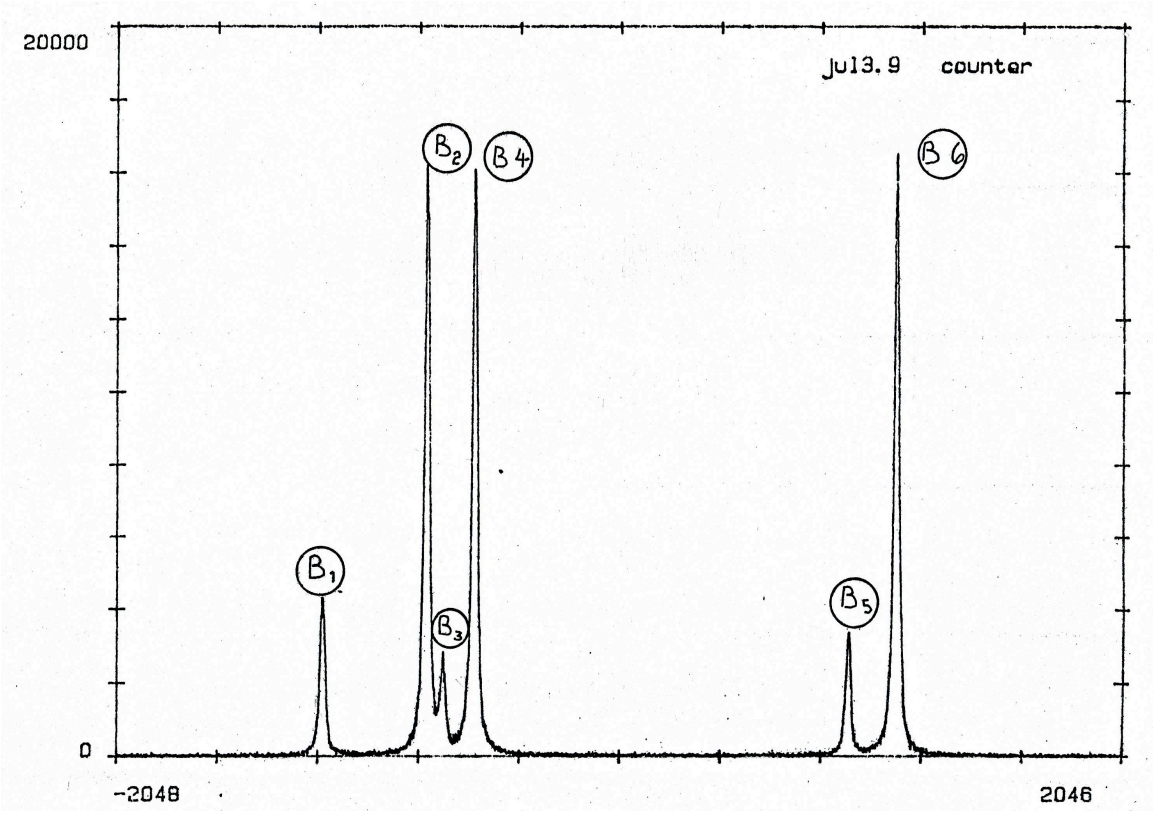

FIG. 10. A reference spectrum of n=2 transitions in lithium. B_5 is the transition we seek, $2S_{1/2}$ (F=1) $\longrightarrow 2P_{1/2}$ (F=1). The intensity (y-axis) is plotted as a function of increasing frequency (x-axis).[11]

In order to detect a small signal in background noise, it is necessary to find a way to turn the small signal on and off at regular intervals. To turn this signal on and off, we use an optical chopper, which is an instrument that resembles a fan with multiple blades. As the optical chopper spins, it chops the light that starts and stops the

transitions. The small signal can be obtained by taking the signal plus background noise when the laser is turned on and subtracting the background noise when the laser is turned off. Using the chopped signal, the lock-in amplifier is capable of locking onto the optogalvanic signals (hence the name, lock-in amplifier).

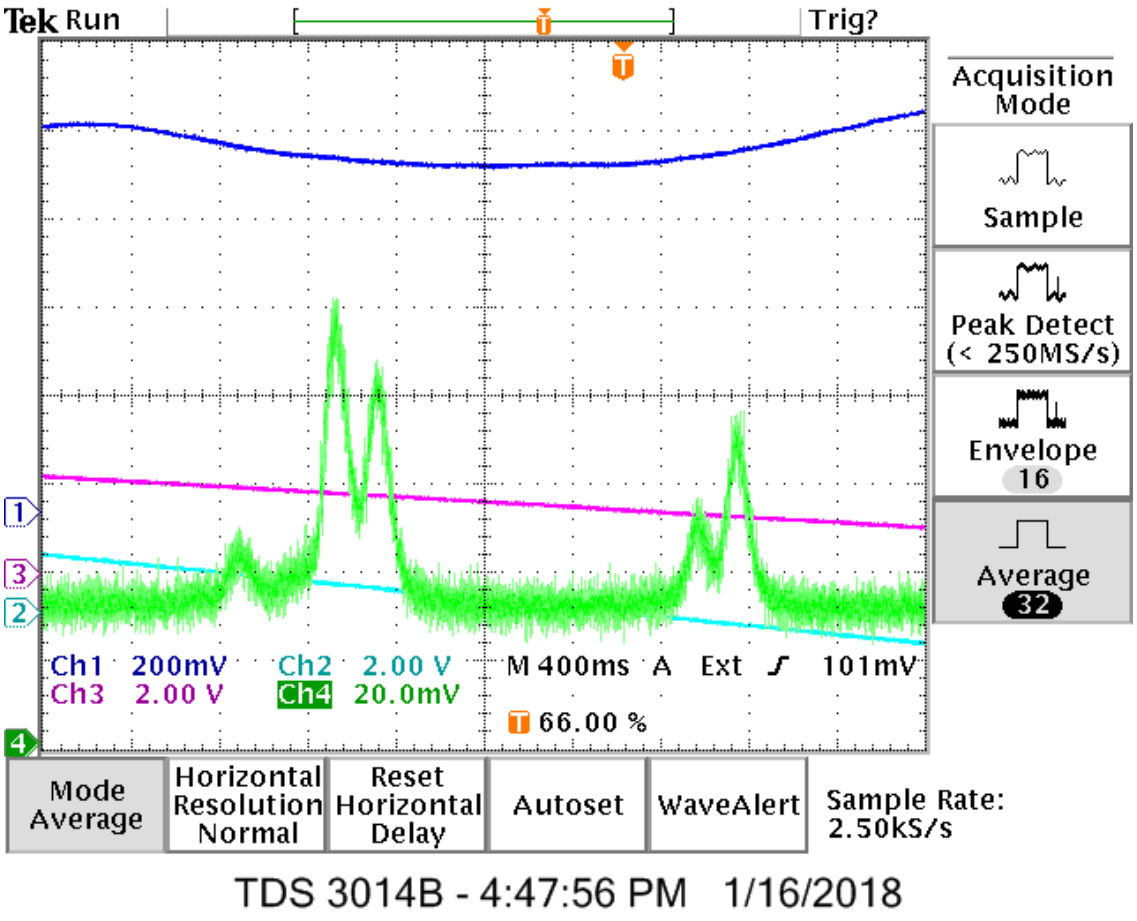

FIG. 11. Our atomic beam scan produces similar signals to the reference scan.

3. Spectrum Analyzer

We use a Coherent 240 spectrum analyzer to observe the performance of the laser. The spectrum analyzer is comprised of two confocal mirrors with high reflectivity. When the frequency of light in the system matches the resonance condition created by the two mirrors, a signal is produced from a photodiode. When the laser is scanning smoothly, the

signals from the spectrum analyzer will be evenly spaced in frequency.[12]

Our spectrum analyzer can be put into scanning mode by applying a time-varying voltage across the "scanning voltage" terminal. This will cause a piezoelectric transducer to change the separation of the mirrors. The spectrum analyzer is designed to scan through one free spectral range of 1.5 GHz when 40 volts is applied. We have built a new driver to provide a safer voltage supply to the spectrum analyzer. The previous spectrum analyzer driver was functional, but would be dangerous if it malfunctioned. If something were to go wrong, a high voltage could be applied across the spectrum analyzer which could break the equipment. In order to achieve a safe, time-varying voltage, we used operational amplifiers (op-amps).

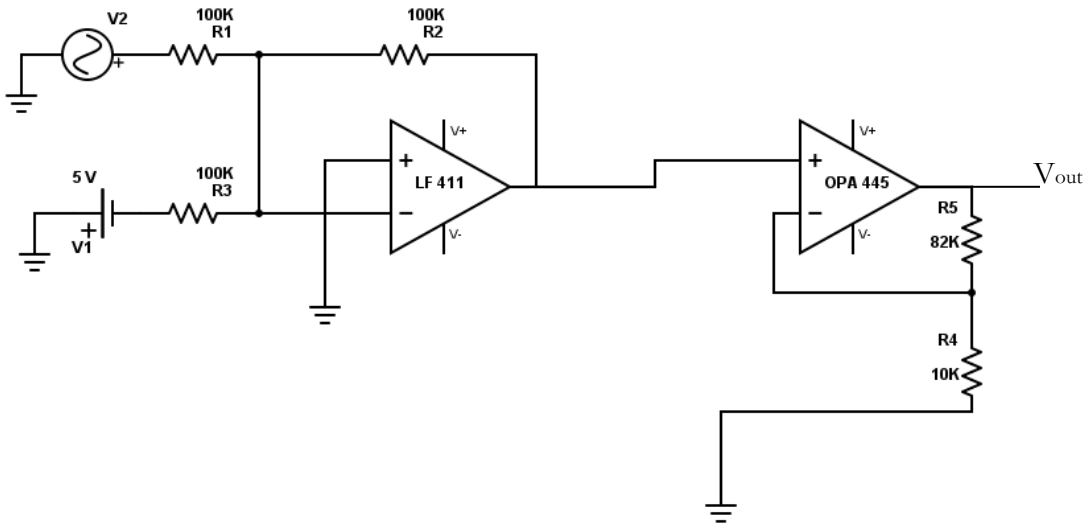

FIG. 12. A schematic circuit diagram of the spectrum analyzer driver. The LF 411 is powered by +/-15 volts and the OPA 445 is powered by +85 volts and -5 volts.

Op-amps with negative feedback obey two "golden rules." The first is that no current flows into the inputs. The second rule states that the inverting and noninverting input voltages are equal.

Using the golden rules, we predict that the output voltage will be given by

$$V_{out} = 46V - 9.2V_2. \quad (12)$$

Using this equation, we predict that an input of – 2 volts, 0 volts, and 2 volts, will result in an output voltage of 64.4 volts, 46 volts, and 27.6 volts respectively.

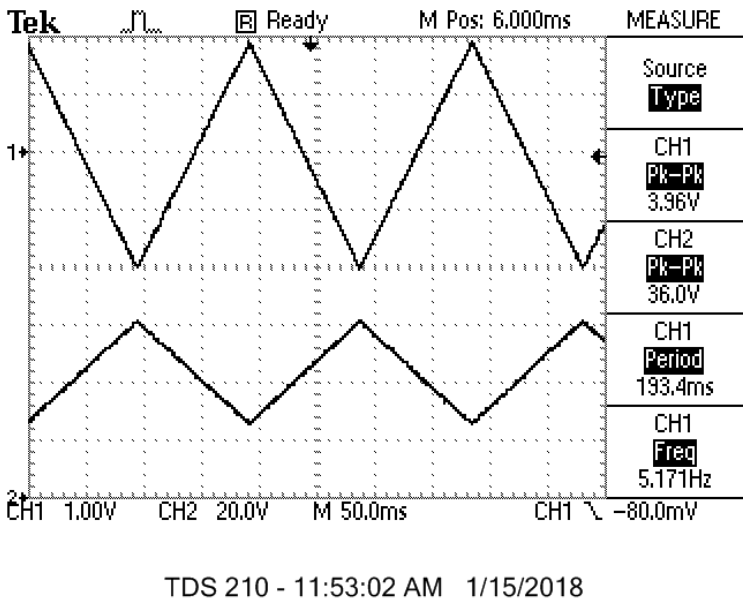

FIG. 13. Channel 1(top) reads the input voltage from a frequency generator. Channel 2 monitors the output of the driver.

Based on the figure above, the driver seems to be behaving adequately for our purposes.

4. Polarization of Light

Photons are wave-like particles of electromagnetic radiation. In free space, the electric and magnetic fields oscillate perpendicular to each other. The polarization of light indicates the orientation at which the electric field oscillates. Most types of light are unpolarized, meaning that there are many oscillating electric and magnetic fields oriented in every direction. A linear polarizer is an optical device that will block all types of light except at one specific polarization. Ideally, the intensity of polarized light after passing through a linear polarizer obeys Malus's Law:

$$I = I_0 \cos^2 \theta. \quad (13)$$

In this equation, θ is the angle between the polarization of the incident light and the transmission axis of the polarizer, I_0 is the intensity of the incident light, and I is the intensity coming out of the polarizer. In our experiment, we need to produce *circularly polarized light*. In circularly polarized light, the polarization of the electric field rotates with consistent amplitude. To produce circularly polarized light, we use a Soleil-Babinet Compensator (SBC).

The SBC is comprised of two wedges and a plate. In this SBC, there is a fast and a slow axis. Light polarized along the fast axis will have a lower index of refraction while light polarized along the slow axis will have a higher index of refraction. A linearly polarized electric field cross-section can be broken up into two equal components along the two axes. The sum of these two vector components gives us a resultant electric field vector which oscillates back and forth in the same direction. If one of these components is retarded by a quarter wavelength, then the resultant vector of the two components will rotate in a circle. Retarding the component by three quarters of a wavelength should also produce circularly polarized light, but rotating in the opposite direction. By convention, right circularly polarized light refers to clockwise circular rotation from the perspective of an observer looking toward the source of the beam. Likewise, left circularly polarized light rotates counter-clockwise when facing the source. In our experiment, we produce both types of circular polarization.

In the first experiments involving EIT, it took a tremendous amount of effort to align two sources of counter-rotating circularly-polarized light with a constant phase difference. In later experiments, it was found that the experiment could be done using

one laser source and two beam splitters. Rather than using two separate lasers, we use one laser and a polarizing cube beam splitter to separate the beam into horizontally and vertically polarized light. The beams are then recombined using another cube beam

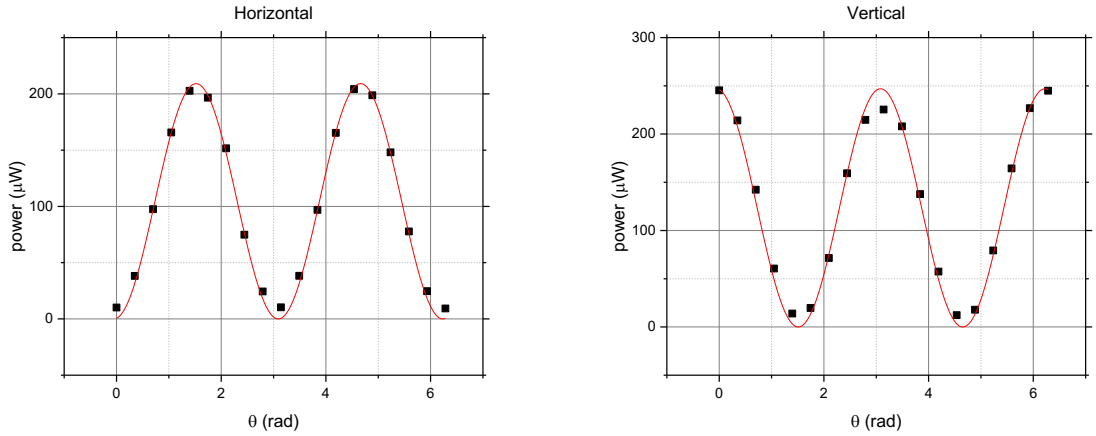

FIG. 14. Graphs of the horizontally polarized light and vertically polarized light intensity as a function of analyzer angle. Both have been fitted to Malus's law. The central maximum in the vertical graph is smaller than what the fit expects. This indicates that the vertical polarizer may not be fully perpendicular to the laser beam.

splitter. Since the two beams originate from the same source, we do not have to worry about the two beams going out of phase. In order to get equal intensities from both beams, we use a half-wave plate. The half wave plate is capable of rotating the angle of polarization with little loss of power.

We can temporarily block one beam of light and attempt to produce circularly polarized light from the remaining beam. Once that is done, the other beam of light will lie 90 degrees out of phase with the first beam. This is functionally equivalent to retarding the wavelength of the beam by three quarters of a wavelength which will produce oppositely circular polarized light.

In order to test for circularly polarized light, we need to cross two polarizers so that the output is extinguished (or as minimized as possible). Then, we place the SBC

between the two polarizers and adjust the fast axis so that the output is again extinguished. By rotating the axis by 45 degrees (either direction will produce the same effect) the fast axis will break up the electric field into to equal components. At this point, some light will be let through. The SBC has a micrometer which adjusts the wedges inside, varying the retardation of the slow axis. We adjust the micrometer so that the spot is again at a minimum and record this setting. We then adjust the micrometer to produce a minimum a second time. After noting these settings, we set the micrometer a quarter (or three quarters) of the way between the two extinguished settings at which point we have circularly polarized light.

In theory, circularly polarized light should pass through a linear polarizer of any angle with the same intensity. We can therefore check the quality of our circularly polarized light by measuring the power as a function of the polarization angle of the second polarizer (called the analyzer). If we have perfect circularly polarized light, the intensity should remain constant. In practice, however, the circular polarization is not always perfect and we obtain light that is slightly elliptically polarized. This means that

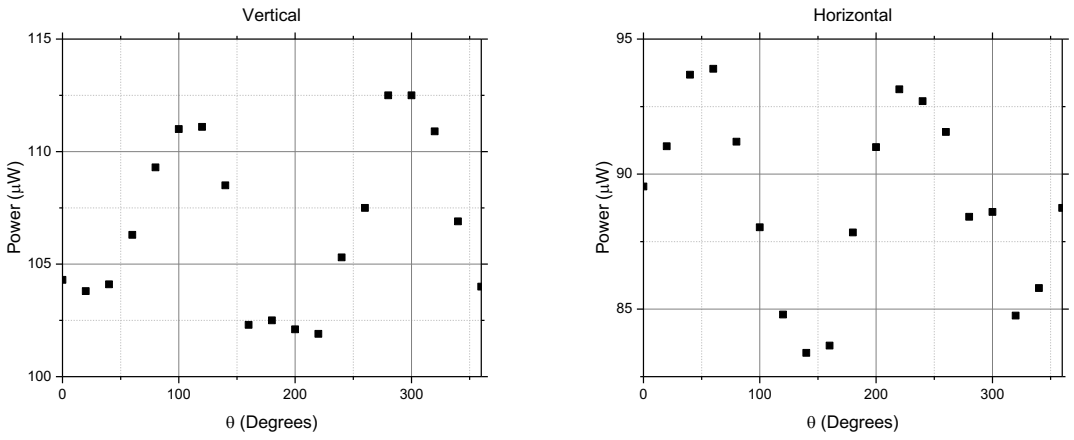

FIG. 15. Graphs of power as a function of analyzer angle with an SBC. The uneven fluctuations suggest that the light is not circularly polarized.

the amplitude of the wave varies as it rotates and the intensity fluctuates as the angle of the analyzer changes.

IV. THEORY OF EIT

In the D_1 transition from F=1 to F'=1 of lithium-7, the upper and lower energy levels both have sublevels of m_F=-1, 0, 1. The selection rules of circularly polarized light dictate that right circularly polarized light can only drive transitions where $\Delta m_F = -1$ and left circularly polarized light can drive transitions where $\Delta m_F = +1$. This system can be approximated as a *lambda configuration*. This configuration is a three state system where there is one upper level, and a lower level with two degenerate states. We will call the upper level $|a\rangle$, and let $|b\rangle$ and $|c\rangle$ be the two lower levels.

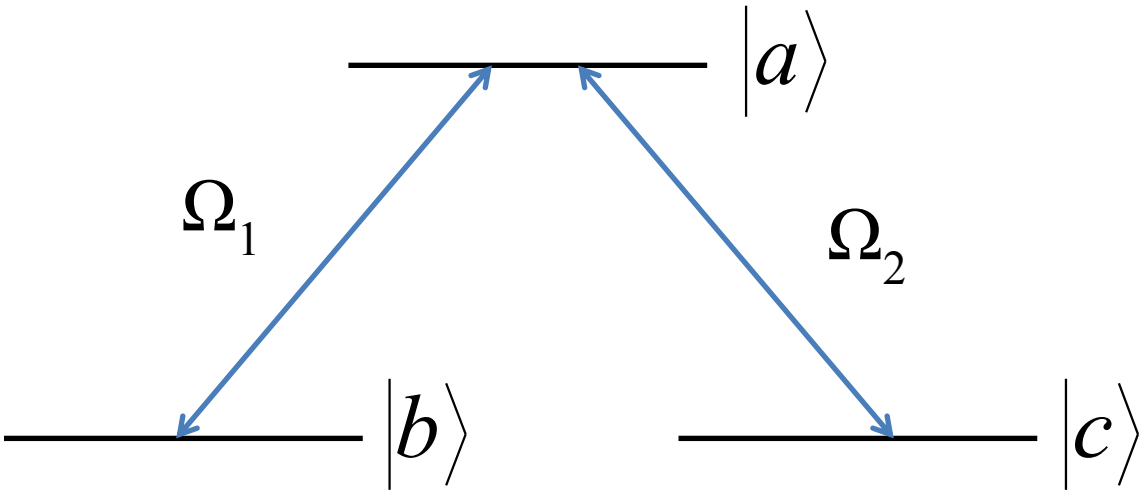

FIG. 16. An adapted diagram of the lambda configuration from Dawson Nodurft's Thesis.[13]

A laser beam can be used to excite the electron from $|b\rangle$ to $|a\rangle$. In this case, the Rabi frequency is given by

$$\Omega_1 = \frac{d_{ab}E_1}{2\hbar}. \tag{14}$$

Here, d_{ab} is the electric dipole moment of the transition from $|a\rangle$ to $|b\rangle$ and E_1 is the amplitude of the electric field from the laser. This laser is called the probe beam. If a second laser beam, called the coupling beam, drives the transition from $|c\rangle$ to $|a\rangle$, then its Rabi frequency will be

$$\Omega_2 = \frac{d_{ac}E_2}{2\hbar}. \tag{15}$$

The Hamiltonian of this system, therefore, will be

$$\widehat{H} = \hbar\Omega_1|b\rangle\langle a| + \hbar\Omega_2|c\rangle\langle a| + \hbar\Omega_1|a\rangle\langle b| + \hbar\Omega_2|a\rangle\langle c|. \tag{16}$$

This Hamiltonian contains terms that represent the absorption that may occur from the lower states to the upper states, and also the stimulated emission that may occur from the upper state to the lower states. Following a derivation from Dr. Yuri Rostovtsev,[14] this can be written as,

$$\widehat{H} = \hbar\sqrt{\Omega_1^2 + \Omega_2^2}\left(\frac{\Omega_1}{\sqrt{\Omega_1^2 + \Omega_2^2}}|b\rangle + \frac{\Omega_2}{\sqrt{\Omega_1^2 + \Omega_2^2}}|c\rangle\right)\langle a| \tag{17}$$

$$+\hbar\sqrt{\Omega_1^2 + \Omega_2^2}|a\rangle\left(\frac{\Omega_1}{\sqrt{\Omega_1^2 + \Omega_2^2}}\langle b| + \frac{\Omega_2}{\sqrt{\Omega_1^2 + \Omega_2^2}}\langle c|\right).$$

This can be simplified to

$$\widehat{H} = \hbar\Omega\left(\frac{\Omega_1}{\Omega}|b\rangle + \frac{\Omega_2}{\Omega}|c\rangle\right)\langle a| + \hbar\Omega|a\rangle\left(\frac{\Omega_1}{\Omega}\langle b| + \frac{\Omega_2}{\Omega}\langle c|\right) \tag{18}$$

where

$$\Omega = \sqrt{\Omega_1^2 + \Omega_2^2}. \tag{19}$$

Essentially, we have changed the basis so that the lower states can be written as two new, orthogonal states which are a combination of $|b\rangle$ and $|c\rangle$. The first will be called the *bright state* which can be written as

$$|B\rangle = \frac{\Omega_1}{\Omega}|b\rangle + \frac{\Omega_2}{\Omega}|c\rangle. \tag{20}$$

Using this bright state, the Hamiltonian can be expressed as

$$\widehat{H} = \hbar\Omega|B\rangle\langle a| + \hbar\Omega|a\rangle\langle B|. \tag{21}$$

The orthogonal *dark state* is defined as

$$|D\rangle = \frac{\Omega_2}{\Omega}|b\rangle - \frac{\Omega_1}{\Omega}|c\rangle. \tag{22}$$

In this basis, the only the bright state is driven to $|a\rangle$. If the atom spontaneously decays to $|B\rangle$, it is pumped back to $|a\rangle$. If the atom decays down to $|D\rangle$ however, the atom becomes trapped.[13]

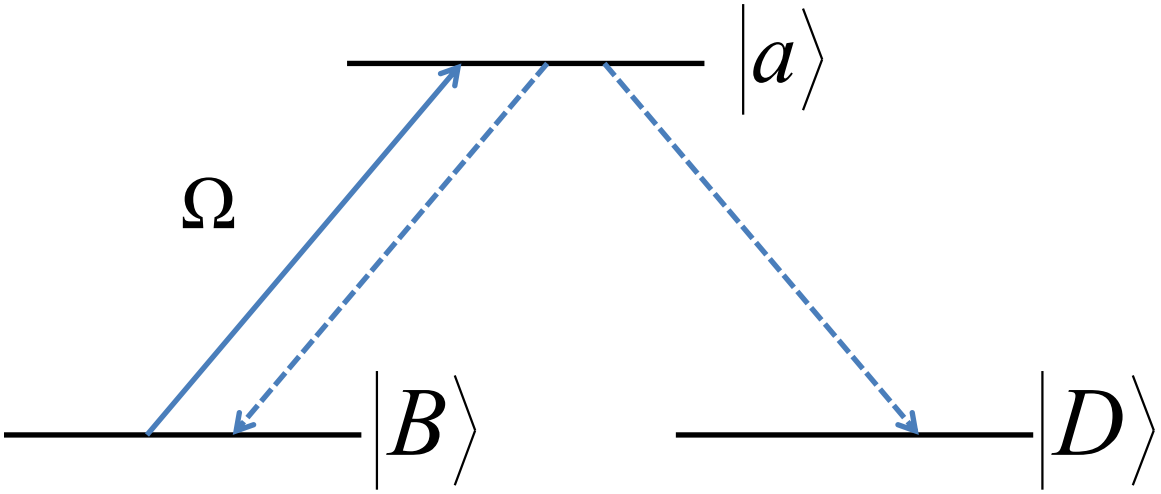

FIG. 17. The bright and dark states are degenerate since they are linear combinations of $|b\rangle$ and $|c\rangle$.

Once the atom is trapped in the dark state, no absorption takes place and therefore no fluorescence can be detected. In the $2S_{1/2} \longrightarrow 2P_{1/2}$ transition from F=1 to F'=1 in lithium-7, there are m_F sublevels as shown in FIG. 18. Circularly polarized light has selection rules that only allow transitions where $\Delta m_F = -1$ for right circularly polarized light, and $\Delta m_F = +1$ for left circularly polarized light.

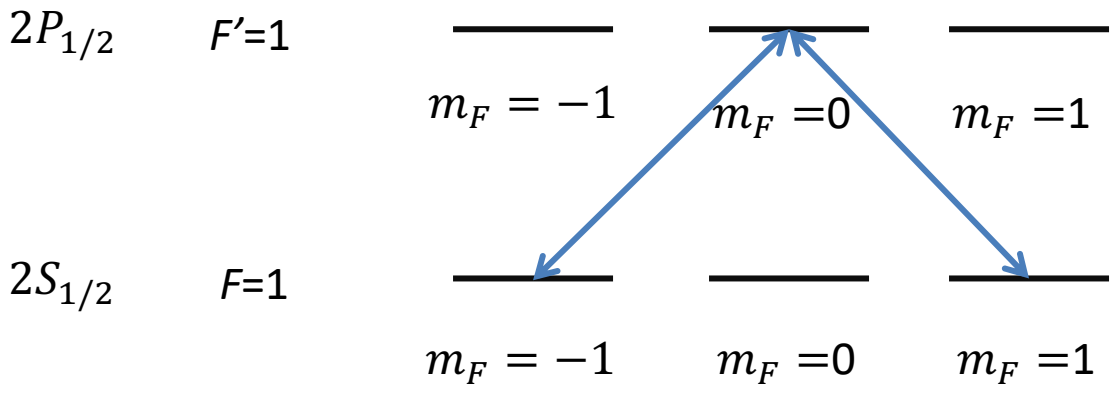

FIG. 18. In the absence of a magnetic field, the m_F values are degenerate and the system can be approximated as a lambda configuration. An applied external magnetic field will shift these sublevels and EIT will not be possible.

V. RESULTS

After eliminating magnetic fields and creating circularly polarized light we attempted to detect EIT. To do so, we first needed to lock onto the $2S_{1/2}$ to $2P_{1/2}$

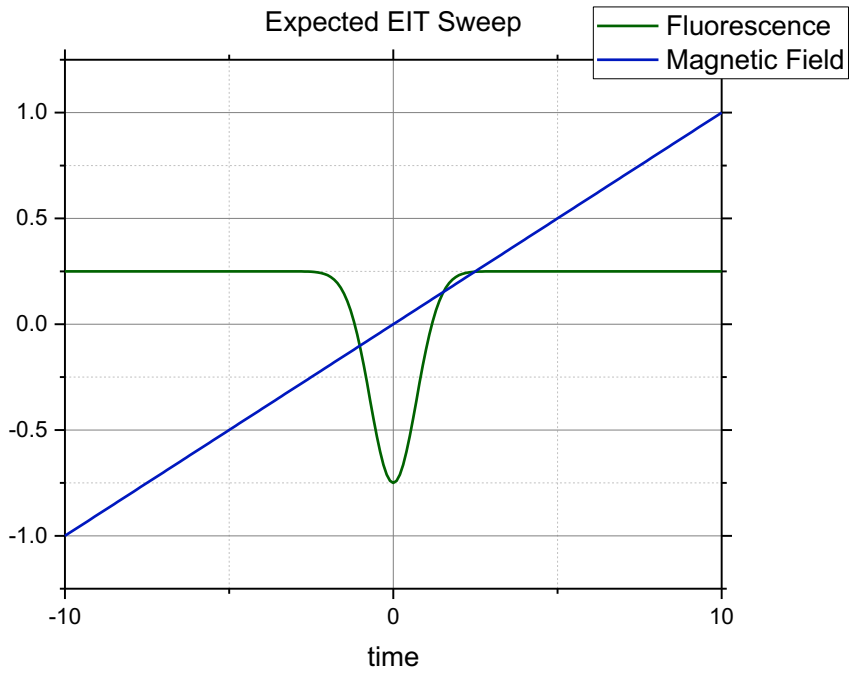

FIG. 19. After the laser has been locked onto a transition, we expect that a dip in signal would occur once the magnetic field reached zero.

transition from F=1 to F'=1. Then, we connected a Pasco function generator to the set of Helmholtz coils in the direction of the laser. We used an oscilloscope to monitor the voltage across a 1 Ω reference resistor in series with the circuit and swept the current in the coils with a frequency of 7 Hz. If we achieved EIT, the fluorescence of the atomic beam should cancel out and we should see a decrease in signal.

When we tried looking for EIT, we were unable to find a clear dip in signal. Although the signal was distorted upward and downward at either end of the sweep, this was not caused by atomic interactions. After we shut off the laser and the oven, we observed that the remaining signal was still distorted at either end.

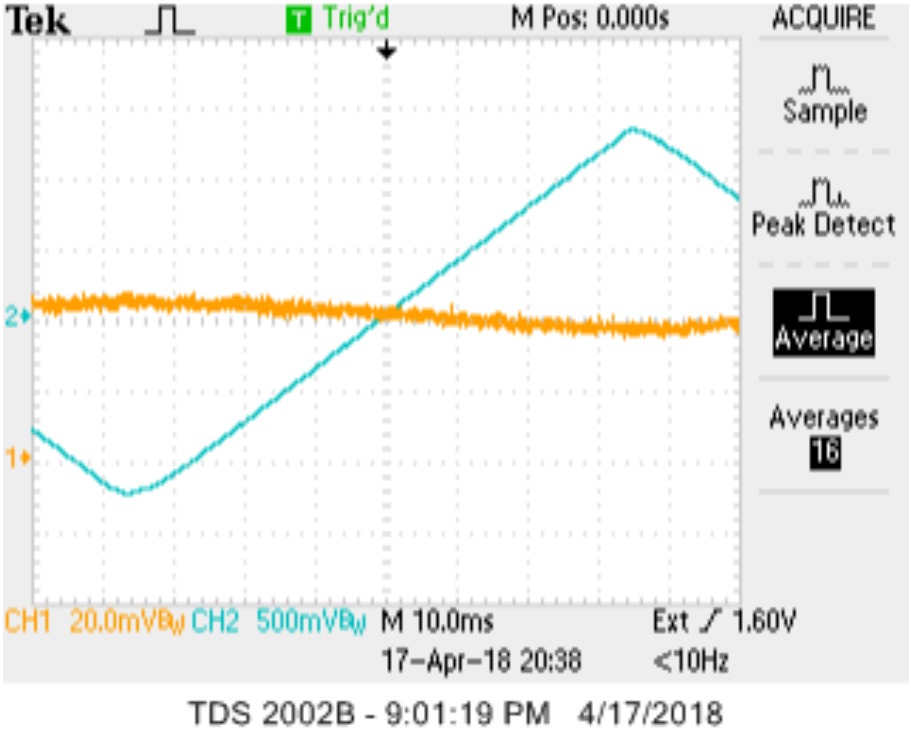

FIG. 20. We expected this scan to resemble previous figure.

Upon further investigation, we found that the width of our peaks was still too wide, despite our efforts to lower the magnetic field. In fact, there was no observable difference between the scans when our Helmholtz coils were set for zero magnetic field and when the coils were turned off. We found that there was only a noticeable Zeeman broadening when a current of 1 amp was applied to a set of Helmholtz coils.

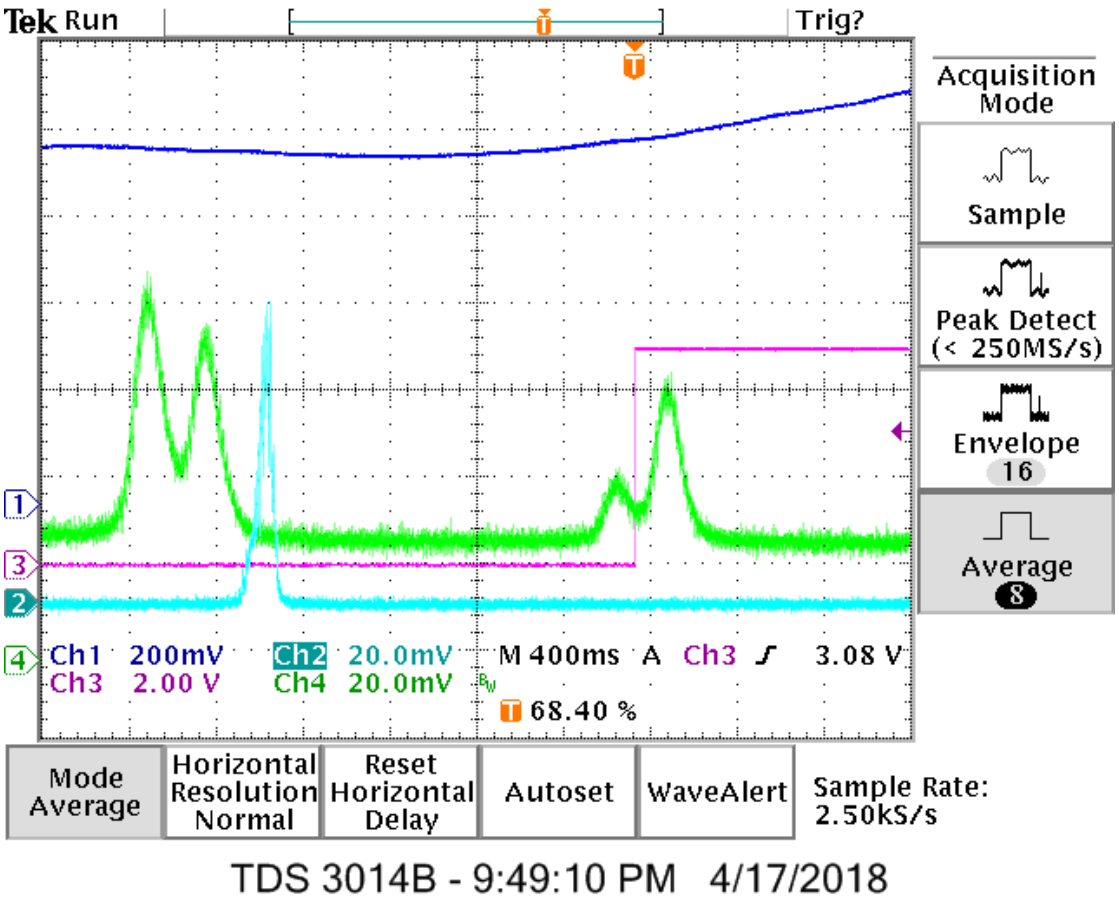

FIG. 21. Scan of fluorescence with 100 mA through the Helmholtz coils. This scan looks the same as a scan with no current through the coils.

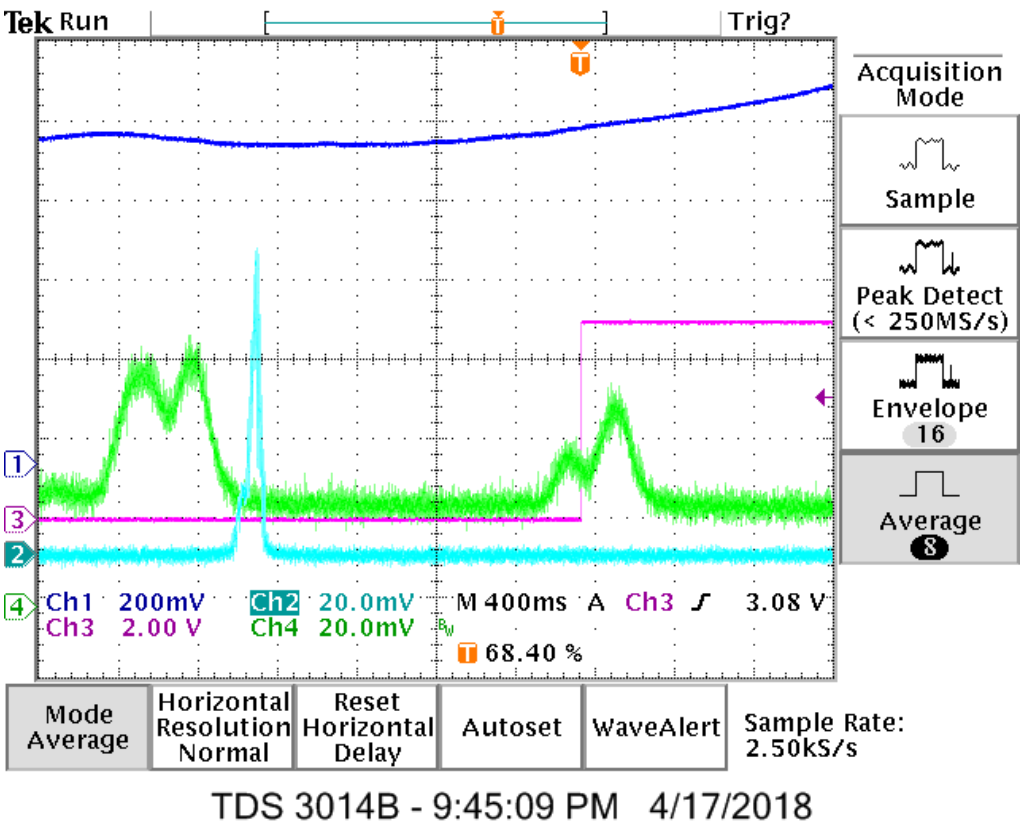

FIG. 22. The transitions broaden after applying 1A through the Helmholtz coils.

This broadening of our transitions means that either we have not successfully eliminated the magnetic fields, or there is another source of broadening that we need to investigate.

Ideally, our laser would emit a single frequency. In reality, however, this is not the case; there is a range of frequencies emitted by the laser. We decided to use a frequency marker from the spectrum analyzer to observe the width of the laser. As seen in the previous two figures, the width of the frequency marker indicated that our laser was emitting a band of frequencies. The width of the band may have been the reason we were unable to achieve EIT. It is also possible, however, that our spectrum analyzer is misaligned or not functioning properly. In the future, the spectrum analyzer should be

checked and calibrated using a helium neon laser.

There are several improvements that can be made to increase the chance of achieving EIT. First, it seems that better alignment of the linear polarizers and the SBC could produce better circular polarization. Another possible improvement is beam density. It may be the case that we need more intense atomic beam. Another technique worth trying is the sweep the magnetic field in a different direction.

Although we have not achieved EIT, we have made significant progress in reducing the magnetic fields and creating conditions favorable for the phenomenon. We have successfully tuned the laser to the desired range of frequencies, and formed an atomic beam. From our work, we have been able to detect fluorescence in lithium and made several attempts at detecting EIT.

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